REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	05 JULY 20065	FINAL REPORT, 01 OCT 2002 - 31 MAR 2006

4. TITLE AND SUBTITLE

Ferrite Materials for Advanced Multifunction Microwave Systems Applications

5. FUNDING NUMBERS

Award No. (Grant) N00014-03-1-0070
PR No. 05PR01353

6. AUTHOR(S)

Carl E. Patton

7. Performing organization name(s) and address(es)

Department of Physics
Colorado State University
Fort Collins, CO 80523-1875

8. PERFORMING ORGANIZATION REPORT NUMBER

None

9. SPONSORING/MONITORINGAGENCYNAME(S) AND ADDRESS(ES)

Office of Naval Research (ONR)
Ballston Centre Tower One
800 North Quincy Street
Arlington, VA 32217-5660

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

None

11. SUPPLEMENTARY NOTES

The view, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Office of Naval Research position, policy, or decision, unless so designated by other documentation.

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

ONR Grant N00014-03-1-0070 has supported a research program with a focus on new materials for applications in the 6-18 GHz range relevant to the AMRFS (Advanced Multifunctional RF systems) Navy program. The program has emphasized three classes of materials, yttrium iron garnet (YIG) and compositional variants, lithium ferrites and compositional variants, and hexagonal ferrites. Polycrystalline and single crystal materials in bulk and thin film form were investigated. These materials were produced by a variety of techniques, including traditional sintering, hot isostatic pressing (HIPPING), liquid phase epitaxy, and pulsed laser deposition. Most materials were obtained as part of collaborations with other university, government, or industrial groups. The pulsed laser deposition thin film work on barium and lithium ferrite was done in-house. Specific measurements included the ferromagnetic resonance linewidth, the high field effective linewidth, the low field effective linewidth, the in-manifold effective linewidth, the spin wave instability threshold microwave field amplitude, and the associated spin wave linewidth. As appropriate for the specific measurement and the sample of interest, data were obtained as a function of frequency, temperature, static and microwave field configuration, and orientation. Time and space resolved Brillouin light scattering and inductive magnetodynamic probe mapping were also used in this work. (200 words)

14. SUBJECT TERMS

Microwave ferrites, yttrium iron garnet, lithium ferrites, hexagonal ferrites, polycrystalline ferrites, single crystal ferrites, thin films, ferromagnetic resonance, ferromagnetic resonance linewidth, effective linewidth, spin wave instability, spin wave linewidth, advanced multifunction microwave systems, time and space resolved magnetodynamics, Brillouin light scattering, hipping, microwave loss, hot isostatic pressing, liquid phase epitaxy, pulsed laser deposition

15. NUMBER OF PAGES

16

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	UL

COVER PAGE

FINAL REPORT
to the
UNITED STATES OFFICE OF NAVAL RESEARCH

Ferrite Materials for Advanced Multifunction Microwave Systems Applications

ONR N00014-03-1-0070, October 1, 2002 – March 31, 2006

Carl E. Patton, Principal Investigator
Jerome J. Green, Co-Principal Investigator
Department of Physics
Colorado State University
Fort Collins, Colorado 80523

Grant Period
01 October 2002 – 31 March 2006

Date of Report:
05 July 2006

Contact Information
Telephone: (970) 491-5083
FAX: (970) 491-7947
E-MAIL: patton@lamar.colostate.edu

A. TABLE OF CONTENTS

B. ABSTRACT

ONR Grant ONR N00014-03-1-0070 has supported a research program with a focus on new materials for applications in the 6-18 GHz range relevant to the AMRFS (Advanced Multifunctional RF systems) Navy program. The program has emphasized three classes of materials, yttrium iron garnet (YIG) and compositional variants, lithium ferrites and compositional variants, and hexagonal ferrites. Polycrystalline and single crystal materials in both bulk and thin film form were investigated. These materials were produced by a variety of techniques, including traditional sintering, hot isostatic pressing (HIPPING), liquid phase epitaxy, and pulsed laser deposition. Most materials were obtained as part of collaborations with other university, government, or industrial groups. The pulsed laser deposition thin film work on barium and lithium ferrite was done in-house. Specific measurements included the ferromagnetic resonance linewidth, the high field effective linewidth, the low field effective linewidth, the in-manifold effective linewidth, the spin wave instability threshold microwave field amplitude, and the associated spin wave linewidth. As appropriate for the specific measurement and the sample of interest, data were obtained as a function of frequency, temperature, static and microwave field configuration, and orientation. Time and space resolved Brillouin light scattering and inductive magnetodynamic probe mapping were also used to investigate these processes.

C. RESULTS

1. Overview

There are few centers of expertise in the world which are capable of quality research and development work in the area of microwave magnetic materials. The Magnetics Laboratory in the Department of Physics at Colorado State University (CSU), Fort Collins, is well equipped for a wide range of high frequency magnetic measurements at low and high power, at low and high field, over a wide range of frequencies, and as a function of temperature. This team also has the resident expertise to select and investigate the critical materials problems that are relevant to the needs cited above. Much of this infrastructure has been established over the past decade with Office of Naval Research (ONR) support.

Past CSU work has addressed and solved numerous microwave loss and materials problems as they relate to both fundamental understanding and device needs. In the area of ferrites, these include (1) the role of microstructure in the low and high power loss properties of polycrystalline yttrium iron garnet (YIG), (2) the low and high power microwave properties of substituted lithium ferrite materials, (3) the microwave properties of arc plasma spray lithium ferrite, (4) the origins of the large losses in hexagonal ferrite materials for millimeter wave applications, (5) the high power microwave properties of hexagonal ferrite materials, (6) the characterization of liquid phase epitaxy yttrium iron garnet (YIG) films produced with special fluxes, (7) the characterization of ultra dense polycrystalline ferrites for microwave applications prepared by hot isostatic pressing (HIPPING) techniques, (8) the growth and characterization of pulsed laser deposited (PLD) ferrite films of YIG and barium hexaferrite with losses which are as good as the best bulk single crystals, and (9) the successful PLD growth of low loss zinc lithium ferrite films.

In the area of metallic ferromagnetic films, which represents a promising system for wide band tunable filters in the microwave and millimeter regime, for example, CSU has been a key contributor to (1) the understanding of phenomenological damping in metal films, (2) the elucidation of microwave loss properties and most recently, (3) a new understanding of the high power properties as well. A significant part of this work has been accomplished during the past and current grant periods under ONR support.

In addition to the above microwave/millimeter wave materials characterization and device physics development work, the Colorado State University program has provided numerous contributions that have advanced the understanding of microwave loss processes and nonlinear spin wave interactions, both for ferrites in general and for thin films in particular. These include (1) a general formulation of the theory of magnetostatic waves in anisotropic magnetic materials, (2) theoretical analysis of spin wave instability processes, both first and second order, for materials with a general ellipsoidal shape, a general anisotropy, and a general pumping field configuration, (3) direct identification of the spin wave interactions responsible for the onset of nonlinear loss in ferrites at high power, and (4) practical theoretical models of the two magnon scattering interaction and calculations of the resulting linewidths and off resonance losses in ferrite materials. A significant part of this work has also been accomplished under ONR support.

2. Education and Human Resources

Personnel supported in whole or in part and degrees granted during the current grant period are indicated below:

Visiting scientists:	5
Postdoctoral fellows:	12
Ph.D. degrees granted:	5
Master of Science degrees:	3
Graduate students:	7
Undergraduate work study students:	4
High school summer apprenticeships:	8

Names, degree specifics, and dates are available on request.

3. Publications and Presentation Statistics

Publications and presentations are listed in Section D. Statistics for the program are indicated below.

Archival journal publications (ONR cited)	8
Archival journal publications (other)	13
Journal articles in preparation (ONR cited)	7
Invited presentations (C. E. Patton):	38
Contributed presentations: (C. E. Patton)	5

Contributed presentations: (other members) 12
The above ONR cited publications include:
IEEE Trans. Magnetics: 2
Journal of Applied Physics: 6

4. Summary of selected results

The purpose of this section is to provide a brief summary of selected work done during the grant period. A full list of publications, presentations, and citations is given in Section D. The results address a variety of issues related to microwave and millimeter wave ferrite materials which play an important role in present devices and offer potential for improved devices for the future. These results lay the groundwork, in part, for the proposed renewal program. The materials have included (1) single crystal hexagonal ferrite films and platelets, (2) dense and conventionally sintered bulk polycrystalline ferrites, (3) low loss single crystal YIG films, (4) single crystal spinel ferrite films, and (5) metallic films. The phenomena have included resonance and off resonance loss, high power properties, and nonlinear effects.

a. Low loss Ba-M hexaferrite films

There have been two main projects during the current funding period related to thin film hexagonal ferrite materials. The most notable one is in the area of pulsed laser deposition (PLD) and the production of low loss state-of-the-art Ba-M hexagonal ferrite films. The CSU group, under the lead of Dr. Young-Yeal Song (Song *et al.*, 2003), built a basic PLD system and produced thin films of both YIG and Ba-M with ferromagnetic resonance linewidths that are as good as in bulk single crystals. The PLD system has a single purpose room in the CSU Magnetics Laboratory that is dedicated to one challenge, the fabrication of ferrite films.

Figure 1 shows a representative FMR spectrum for a 0.85 μm thick Ba-M film deposited on (0001) sapphire. The frequency was 60.3 GHz and the film was saturated with a static magnetic field perpendicular to the film plane. The most noteworthy result from Fig. 1 is the extremely narrow FMR linewidth, as evident from the expanded data for the main peak shown in Fig. 2. This derivative linewidth of 16 Oe converts to a half power linewidth of 28 Oe. This is the lowest barium ferrite thin film linewidth ever reported. It matches, moreover, the linewidths obtained for bulk platelets of barium ferrite. The X ray diffraction rocking curve for this film has a width of 0.15°. These combined results show that the CSU ONR program has produced one long sought after goal, single crystal barium ferrite thin films with properties which are essentially the same as bulk. The key to the breakthrough in microwave linewidth is in the careful optimization of deposition and annealing conditions.

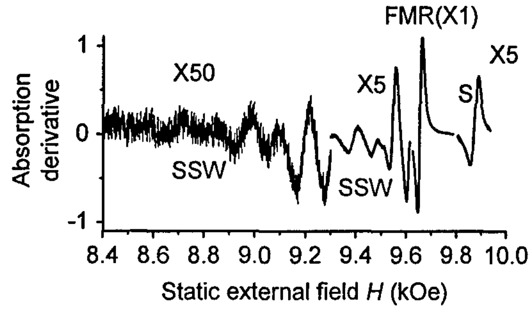

FIG. 1. Full ferromagnetic resonance (FMR) and spin wave resonance absorption derivative versus the static external field H for the 0.85 μm thick film at 60.3 GHz. Response regions above and below the main FMR mode are shown on an expanded vertical scale, as indicated. The weak mode at a field above the FMR mode is labeled S to indicate a possible surface mode. The modes below the FMR mode are labeled SSW to indicate standing spin wave modes. [Y. Song, S. Kalarickal, and C. E. Patton, J. Appl. Phys. **94**, 5103 (2003).]

Figure 3 shows additional results on the half power FMR main mode linewidth as a function of frequency. The circles show data for the same film used for the results presented above. The squares show published data on half power FMR linewidths for bulk single crystal BaM platelets, from Karim *et al.* (1993). The

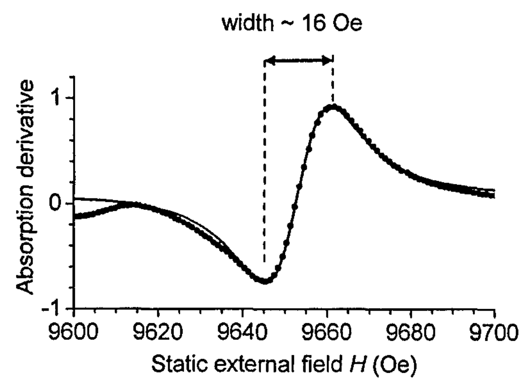

FIG. 2. Expanded view of the absorption derivative versus static external field H at 60.3 GHz for the main ferromagnetic resonance mode labeled FMR in Fig. 3. The solid circles show the data. The solid line shows a fit to the data based on a Lorentzian absorption response with a resonance field of 9653 Oe, a half power linewidth of 28 Oe, and an 11% baseline shift. Y. Song, S. Kalarickal, and C. E. Patton, J. Appl. Phys. **94**, 5103 (2003).]

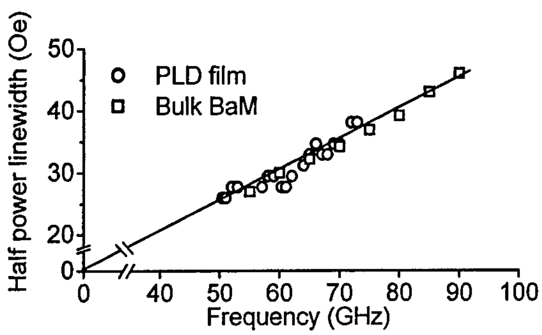

FIG. 3. Half power linewidth for the main ferromagnetic resonance mode versus frequency. The circles show the linewidth data for the 0.85 μm thick PLD BaM film used for the results in the previous figures. The squares show data from Ref. 12 for a bulk BaM single crystal platelet. The line represents a linear fit of all the data. [Y. Song, S. Kalarickal, and C. E. Patton, J. Appl. Phys. **94**, 5103 (2003).]

line shows a linear fit to all the data. The linear fit in Fig. 5 has a slope of 0.5 Oe/GHz and a zero frequency linewidth intercept of zero. While the film data show a fair amount of scatter, it is clear that the thin film linewidths track the results for the bulk platelets. These data represent one of the key results of the current program, namely, that the linewidth for the optimized PLD BaM films matches that of bulk single crystal BaM.

The 0.5 Oe/GHz linewidth response is also significant. As a point of reference, note that the half power FMR linewidth in single crystal yttrium iron garnet (YIG) typically has a response of 0.05 Oe/GHz and an extrapolated linewidth of zero at zero frequency. If the data in Fig. 3 are assumed to represent intrinsic losses, the response implies that such losses are a factor of ten greater than for YIG. This factor of ten result, combined with the fact that the single crystal film data fall on top of the bulk platelet data, show that major problems remain if one is to produce hexagonal ferrite films with losses close to that for YIG. CSU work on the spin wave linewidth in planar Zn-Y hexagonal ferrites is presented below. These data indicate the clear role of anisotropy in spin wave losses. One approach to avoid such losses may be to work off resonance, where losses due to inhomogeneities are small. The concept of an off resonance or effective linewidth will be discussed below.

b. Anisotropy driven loss in Zn-Y hexaferrite platelets

Single crystal platelets of planar anisotropy Zn-Y type hexagonal ferrite have proven to be an extremely useful test bed to investigate the origin of the microwave losses in the high anisotropy hexaferrite system. Figure 4 (Nazarov *et al.*, 2003a) shows one key result from these investigations. Here, data are shown on the spin wave linewidth ΔH_k as a function of the magnetization angle with respect to the platelet normal, θ_M, for a pumping frequency of 16.7 GHz. The frequency of the spin waves is one half this value. The solid squares, solid circles, and open squares show the results for the three experimental θ_H values of zero, 5°, and 10°, as indicated. The single solid diamond point at $\theta_M = 90°$ corresponds to the parallel pumping spin wave linewidth for an in-plane field of 1 kOe. The horizontal dashed line for $\Delta H_k = 12.8$ Oe is included to show a point of reference for the constant spin wave linewidth from the in-plane field case.

The main result here is that the spin wave linewidth increases significantly as the magnetization vector **M** is pulled out of the easy plane. For θ_M values above 70° or so, ΔH_k is at its minimum value which has been matched to the in-plane field value of 12.8 Oe. As θ_M falls below 70°, ΔH_k increases. The spin wave linewidth then shows a broad peak at $\theta_M \sim 40°$ and a maximum ΔH_k of about 19 Oe. As θ_M is further reduced, this peak is followed by a local minimum at $\theta_M \sim 25°$ with $\Delta H_k \sim 16.5$ Oe. For $\theta_M < 20°$, ΔH_k increases rapidly.

The fact that the spin wave linewidth changes as the magnetization vector is pulled out of plane is not surprising. The relaxation processes which give rise to ΔH_k in the first place derive from fundamental magnon-magnon and magnon-phonon interactions (Gurevich *et*

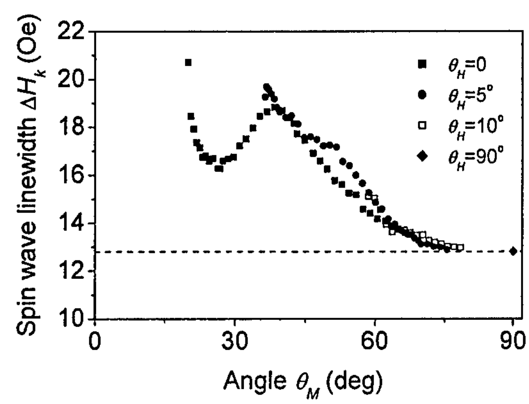

FIG. 4. Spin wave linewidth ΔH_k versus the static magnetization equilibrium angle θ_M for the Zn-Y disk at 8.35 GHz. The symbols show ΔH_k values extracted from the spin wave instability threshold field h_{crit} data for experimental θ_H values, as indicated. The horizontal dashed reference line corresponds to a constant ΔH_k at 12.8 Oe. [A. V. Nazarov and C. E. Patton, J. Appl. Phys. **93**, 9195 (2003).]

al., 1999). Magnon-phonon processes derive from spin orbit interactions which change as the direction of **M** changes relative to the crystallographic axes. Magnon-magnon processes will also change with θ_M because of the shift in the spin wave band position (Gurevich and Melkov, 1996). Any linewidth contribution associated with these processes changes as **M** is pulled out of the crystallographic easy plane for the Zn-Y disk.

Specific connections are possible. First of all, one can exclude inhomogeneities as a source of this response. Two magnon processes should *not* have a large effect on the spin wave linewidth, especially in single crystals. Rather, the mechanism should be related to the large magnetocrystalline anisotropy, spin orbit coupling, and magnon phonon processes. A connection with spin orbit processes and magnon-phonon relaxation is certainly plausible here. The large anisotropy for the Zn-Y material originates from a strong spin orbit interaction. Moreover, it is well known that a strong spin orbit interaction causes an increase in both the FMR linewidth and the spin wave linewidth.

It is important to emphasize here that the results in Fig. 4 constitute the first observation of an angular dependence for the *spin wave linewidth* in *any* magnetic materials. There have also been no previous theoretical predictions of such an effect and the exact mechanism has yet to be elucidated. The impact of this effect may be far reaching. One can expect, for example, a similar ΔH_k response in other high anisotropy materials such as uniaxial Ba-M hexagonal ferrite. In fact, the FMR linewidth in Ba-M disks shows an angular dependence which is similar to that found for Zn-Y. This discovery may also be relevant to large angle switching experiments in anisotropic materials. The data here suggest that the applicable damping will change as the magnetization vector changes its direction relative to the crystal axes during switching.

c. Near theoretical loss in dense bulk polycrystalline ferrites

Porosity is one well known cause of microwave loss. For YIG, as an example, one obtains a 10 GHz FMR linewidth of about 20 Oe per percent porosity. In standard sintered materials, one must usually grow the grains in order to reduce the porosity. Small grains, however, are better than large grains for high power. This is because small grains produce a larger effective spin wave linewidth due to transit time limitations. The end result is that fine grains give a corresponding high power handling capability. As part of the ONR program, one project has been undertaken to examine polycrystalline ferrites produced by hot isostatic pressing (HIPPING to achieve materials with both small grains and a near zero porosity.

The work accomplished to date was done on closed pore polycrystalline YIG sintered from conventional starting powders to a relatively large grain size of 8 μm, and then subjected to the HIPPING process to produce an ultra dense polycrystal. The data shown below were obtained in collaboration with Drs. Jerome J. Green, the co-PI on this program, H. Jerold Van Hook, a private microwave consultant previously associated with Raytheon Company, Gil Argentina of Pacific Microwave, and Bodycote, Inc. Work is in progress to use the HIPPING of fine grain materials to achieve extraordinary high power handling capability. The production of fine grain HIPPED ferrites for high power microwave applications is one of the focus points of the renewal program. The summary here is limited to the low power linewidths only.

Figure 5 (Nazarov *et al.*, 2003b) shows representative linewidth versus frequency results for a HIPPED YIG sphere. The solid points show the data. The solid curve shows the computed linewidth for two magnon scattering due to randomly oriented single crystal grains with the anisotropy within each grain taken to be the same as for YIG single crystal. The well known and well used theory is due to Schloemann (Schloemann, 1958). The dotted line shows a small upward shift to account for the intrinsic losses. These data represent the first experimental confirmation of the predicted linewidth frequency response. Up to now, it has not been possible to make polycrystalline YIG materials dense enough to see the pure anisotropy

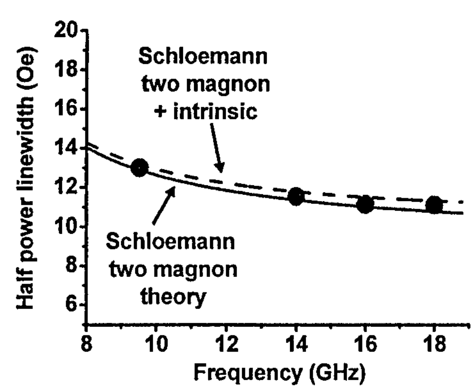

FIG. 5. Ferromagnetic resonance linewidth versus frequency for a HIPPED YIG sphere. [after A. V. Nazarov, D. Ménard, J. J. Green, and C. E. Patton, J. Appl. Phys. **94**, 7227 (1993).]

scattering linewidth along due to the presence of residual porosity scattering. As stated above, a one percent porosity would add about 20 Oe to these linewidths at 10 GHz and would add 40 Oe at 20 GHz. These HIPPED YIG materials clearly have a very small porosity, if any.

These data show the power of the HIPPING process to produce dense ferrites for fundamental loss studies as well as practical low loss devices. It is clear that this process is very promising for the production of low loss polycrystalline ferrite materials. The next and crucial step will be in the production of a very small grain size at near theoretical density and the consequent realization of extremely high power materials.

d. Foldover and bistability in single crystal YIG films

Section b above touched on the use of high power measurements in the study of microwave loss properties. High power often produces another effect termed "foldover." This can occur through the classical nonlinear response, parametric spin wave generation, or classical heating effects. One often sees a distortion of the main ferromagnetic resonance absorption profile in which the peak first shifts and steepens on one side, and then evolves into a bistable response. Example curves of the computed FMR loss versus frequency at different powers and versus power at different frequencies for a perpendicularly magnetized YIG film at fixed field are shown in Fig. 6 (Fetisov and Patton, 2004). This particular example is for thermally driven foldover. One can see that the effect can be quite severe. This type of response can be desirable, as for a bistable microwave switch, for example, or undesirable, when one desires a high Q tunable filter, as another example.

Figure 7 shows a schematic of the microwave structure and set-up for actual measurements. Figure 8 shows actual data. The YIG film microstrip line structure is similar to the configuration of tunable thin film FMR notch filters, limiters, and other high Q YIG film devices. Figure 8 shows a typical low power FMR response in the top panel, and the effect of an increase in power in the foldover and bistable response in the lower panels.

The data in Fig. 8 show the characteristic thermal foldover response. The trace for $P_{in} = +7$ dBm in (a) shows a small shift and an asymmetric distortion from the narrow and symmetric main peak profile at very low power. These changes develop continuously as the

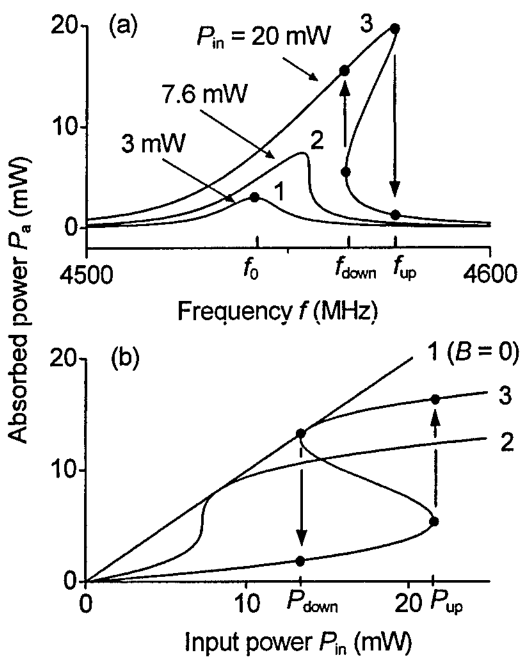

FIG. 6. Graphs (a) and (b) show calculated foldover and bistability profiles of the absorbed power P_a versus frequency f and the input power P_{in}, respectively, for a perpendicularly magnetized YIG film with a low power linewidth $\Delta f = 17.6$ MHz and biased to give a low power FMR peak at 4540 MHz. Curves 1, 2, and 3 in (a) and curves 2 and 3 in (b) are for a power frequency response parameter $B = 1.83$ MHz/mW. Curves 1, 2, and 3 in (b) are for f – values of 4540 MHz, 4555.2 MHz, and 4570 MHz, respectively. [Y. K. Fetisov and C. E. Patton, IEEE Trans. Magnetics **40**, 473 (2004).]

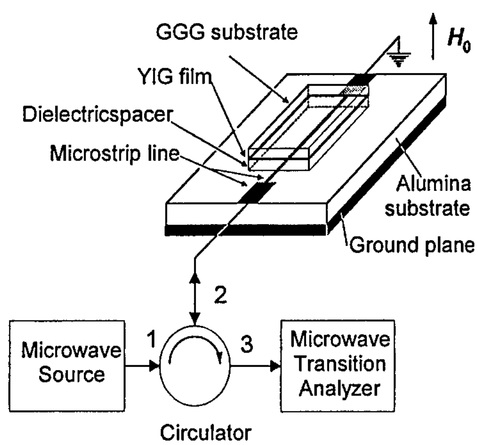

FIG. 7. Schematic of the yttrium iron garnet (YIG) film resonator and the microwave measurement system. The film is upside down on a gadolinium gallium garnet (GGG) substrate and is separated from the microstrip line by a dielectric spacer. The static field $\mathbf{H}_0$ is applied perpendicular to the film plane. [Y. K. Fetisov and C. E. Patton, IEEE Trans. Magnetics **40**, 473 (2004).]

power is increased from the low power reference level of 1 mW (0 dBm). There is no hysteresis.

As soon as the power is increased above +7 dBm, one finds several abrupt and discontinuous changes from the trace shown in Fig. 8(a). There is a splitting in the up-sweep and down-sweep traces and the appearance of hysteresis. As the power is increased, the up-sweep trace also develops a very large asymmetry and continues to shift up in frequency. The high frequency edge of the profile becomes very sharp. At the same time, the down-sweep exhibit traces only a sharp cusp response that shifts to higher frequency as P_{in} is increased. The down-sweep cusps always remain well below the steep high frequency edge of the up-sweep traces.

The thermal foldover effects evident in Fig. 8 can be quantified through further measurements of the absorption ratio of the peak FMR loss to the input power and the two jump point frequencies f_{up} and f_{down} as a function of power. Based on such measurements, one can obtain computed response curves of the sort shown in Fig. 6. One reviewer of this

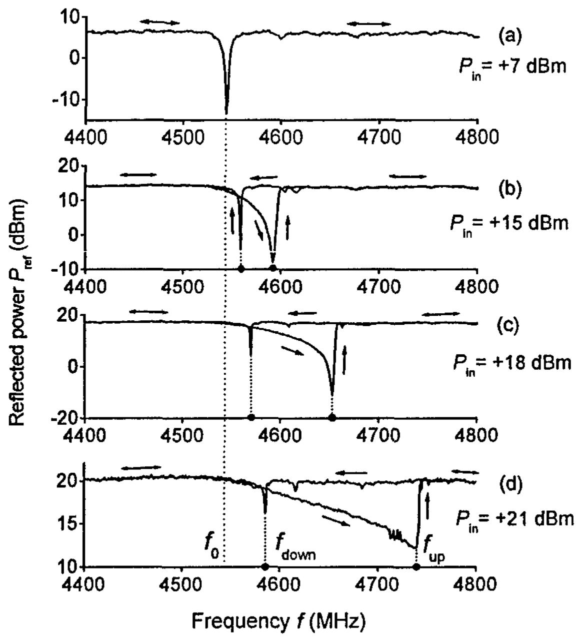

FIG. 8. Reflected power P_{ref} as a function of the frequency f for the YIG film resonator at various levels of input cw power P_{in}, as indicated. The arrows show the directions of the traces for the up-sweep and down-sweep profiles, as indicated. The vertical dotted line across all the panels shows the position of the main resonance at frequency f_0 for low power. The f_{up} and f_{down} frequency jump points for panels (b) - (d) are indicated by solid circles and dotted lines and labeled in panel (d) only. [Y. K. Fetisov and C. E. Patton, IEEE Trans. Magnetics **40**, 473 (2004).]

IEEE paper called the work a "tour de force" on FMR foldover in single crystal films.

e. Off resonance effective linewidth

The off resonance effective linewidth provides a useful measure of the actual losses that affect the insertion loss of real polycrystalline ferrite microwave devices such as circulators and phase shifters. Some of the basics will be discussed in Part II as part of the proposed new work and measurement methods. A long standing challenge has been the seeming contradiction between the expectation of effective linewidth values in the high field limit that should approach near intrinsic single crystal linewidths and the reality of a much larger value that depends on the microstructure.

New high accuracy measurements have resolved this dilemma. Careful and insightful measurements by Ph.D. Candidate Nan Mo on polycrystalline YIG materials have revealed a high field effective linewidth that decreases with increasing field and extrapolates to a high field limit value that is very close to the expected linewidth for single crystals.

Figure 9 shows the essential results. Here, the 10 GHz high field effective linewidth, ΔH_{eff}, for (a) HIPPED ultra dense YIG and (b) conventionally sintered nominally dense YIG spheres is shown as a function of the field. The solid lines show the calculated variation in the total degenerate magnon density of states (DOS), scaled to match the high field data. The error bars show the accuracy of the measurements.

The good match between the data and the DOS curve in (a) shows that field dependence of ΔH_{eff} and DOS response track nicely for ultra dense YIG. This is the same material used above for the FMR linewidth data and full two magnon analysis for degenerate spin waves within the conventional spin wave band. There is also a good match in (b) for fields down to the H_{00}^{*} field point at about 5.6 kOe. These matches indicate a new and previously unrealized result, that two magnon scattering into low wave number electromagnetic branch spin wave (EMSW) excitations plays a key role in the high field response. These modes, and their role in the high field losses, have been ignored for over 35 years! The fact that the data in (b) rise sharply above the DOS curve for fields below H_{00}^{*} provides further support for this ΔH_{eff} - EMSW connection. The H_{00}^{*} marks the field below which spin waves in the conventional spin wave band become degenerate with the uniform mode and allow the usual two magnon process to begin to come into play.

The other point of note from Fig. 9 is that the high field limit values of ΔH_{eff} in both cases are very close to the known 10 GHz intrinsic linewidth in single crystal YIG of 0.5 Oe. In the extreme high field limit, the DOS response for the EMSW modes goes to zero and one expects no two magnon contribution to the linewidth. One expects, therefore, a high field limit effective linewidth that is the same as the intrinsic value. For the first time in 35 years, these data confirm this expectation.

Recent work has focused on the low field effective linewidth. Low field is the regime of choice for many off-resonance devices because of the relative ease in obtaining the needed fields. Data are shown in Fig. 10. The format is the same as for Fig. 9. Here one sees the high field tail response above the manifold region as in Fig. 9. But one also sees a rather interesting low field response. For this low field response, the data for the HIPPED and CS materials are now inverted. The ultra dense HIPPED YIG has a higher low field ΔH_{eff} than does the more porous CS sample. There is also a notable elbow in the field response for both sets of data at a common field labeled as H_X in the figure. These data represent the first comprehensive low field effective linewidth data ever taken. The field responses and the elbow effect in particular provide yet another signature of the importance of the EMSW modes for effective linewidth.

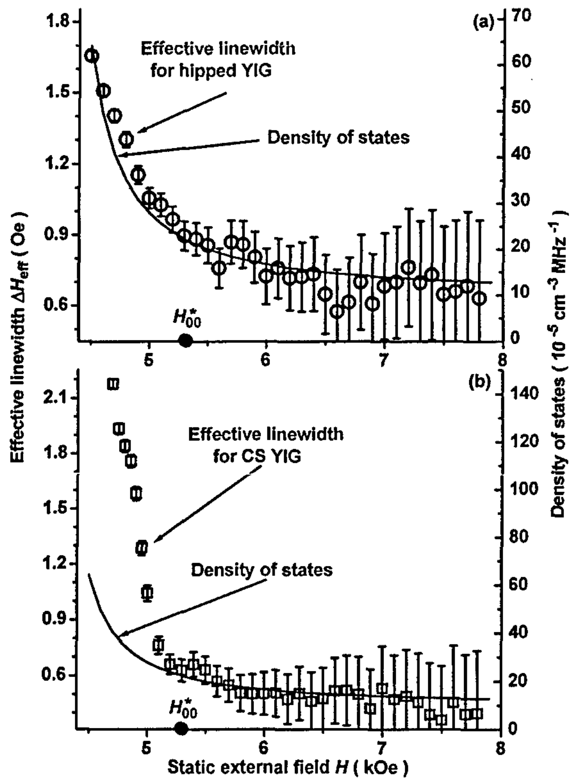

FIG. 9. Graphs of the high field effective linewidth ΔH_{eff} and the total electromagnetic spin wave density of states as a function of the static external field. The open circles in graphs (a) and (b) and the corresponding error bars show the measured effective linewidth data for the HIPPED and conventionally sintered (CS) YIG samples, respectively. The solid curves show the calculated density of states for degenerate electromagnetic spin wave modes at the signal frequency, as a function of the field. The H^*_{00} point indicates the effective band edge field when the dipole field of spherical pores is taken into accounted. [N. Mo, Y. Song, and C. E. Patton, J. Appl. Phys. **97**, 093901 (2005).]

Figure 11 shows a schematic plot of the full spin wave band in a wave number k versus external field format for YIG materials and a spin wave frequency of 10 GHz, chosen to match the modes that would be degenerate with the driven FMR mode when excited at 10 GHz. The label DEL denotes the usual dipole exchange spin wave band, while EML and EMA denote the Larmor and anti-Larmor electromagnetic spin wave bands, respectively. Note that at high field, one has only the tails of the DEL and the EMA bands degenerate with a 10 GHz microwave drive. The DOS response for these tail modes is responsible for the response in Fig. 9. Note also that at low field, one has a critical point at $H = H_X$ for which degenerate modes

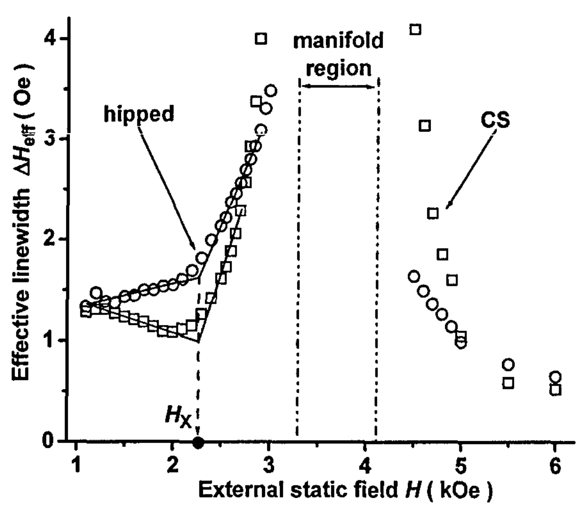

FIG. 10. Effective linewidth ΔH_{eff} as a function of static external field H at a nominal operating point frequency 10 GHz for the HIPPED YIG and CS YIG spheres with nominal diam 2mm. The open circles and the open squares show data of the HIPPED YIG and the CS YIG, respectively. The vertical dash-dotted lines indicate the spin wave manifold. The solid lines are used to linearly fit selected data above and below the elbow point field H_X. [N. Mo, J. J. Green, P. Krivosik, and C. E. Patton, 49th Conference on Magnetism and Magnetic Materials, 8 - 11 November 2004.]

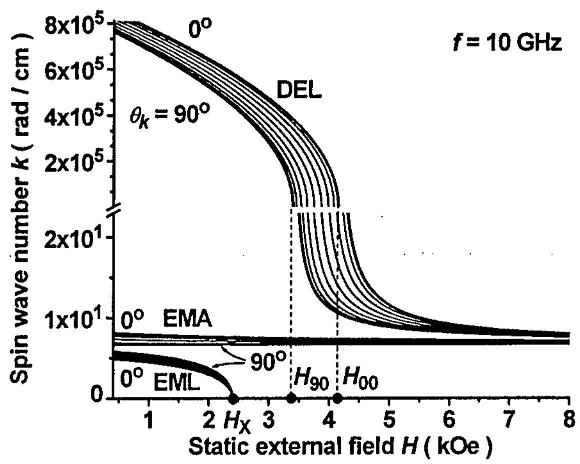

FIG. 11. Diagram of the three spin wave bands in a wave number versus field format for fixed frequency. The graph shows curves of the spin wave number k as a function of the static external field H at a fixed frequency f of 10 GHz for the full range of propagation angle θ_k from 0° to 90°, as indicated. The curves group into three bands, the dipole exchange Larmor (DEL) band, the electromagnetic Larmor (EML) band, and the electromagnetic anti-Larmor (EMA) band, as indicated. The graph shows three important field points along the H – axis, an H_X field that corresponds to the top field of EML band, the moderate k band or spin wave manifold limits in field at $H = H_{90}$ and $H = H_{00}$. [N. Mo, J. J. Green, P. Krivosik, and C. E. Patton, 49th Conference on Magnetism and Magnetic Materials, 8 - 11 November 2004.]

come in from the EML spin waves. For higher fields, one has only extremely high k modes from the DEL manifold and low k modes from the EMA manifold. One can clearly associate the elbow effect in Fig. 10 with the H_X point in Fig. 11. The inverted microstructure effect for the low field response, relative to the high field effective linewidth, must be related to the enhanced strength of high k -scattering for the ultra dense HIPPED YIG material. This could be due to grain boundary scattering. These high k modes are not available at high field.

Further work to quantify the low field effective linewidth response and develop a full theory of two magnon scattering out of the manifold region is in progress. These connections are expected to play a significant role in the understanding of off resonance losses and the development of thick and thin polycrystalline ferrite films for low loss phase shifter and circulator applications.

f. Pulse laser deposited lithium zinc ferrite films

While yttrium iron garnet is perhaps the microwave ferrite material with the lowest loss, the drawback of a relatively low nominal saturation induction ($4\pi M_s$) of 1750 G has generally led to the use of spinel materials such as lithium zinc ferrite for the higher microwave frequency regime where one can take advantage of the higher $4\pi M_s$ values of 3000 - 5000 G. The production of lithium ferrite films, however, with an adequately low loss has generally presented a serious problem. The CSU group has recently made significant progress in this area by growing lithium zinc ferrite (LZF) films on MgO substrates by pulsed laser deposition (Song *et al.*, 2005). Fortuitously, the group had several small blocks of $Li_{0.5-x/2}Zn_xFe_{2.5-x/2}O_4$ with different zinc levels on hand from previous programs. It turns out that the lattice parameter of LZF materials at $x = 0.6$ provides a better match to that of MgO than pure lithium ferrite.

While not on par with single crystal losses, the PLD films recently produced have 9.5 GHz half power linewidths as low as 57 Oe and other properties commensurate with good single crystals. Figure 12 shows a representative 9.5 GHz FMR derivative absorption profile for a 0.70 μm thick film. The FMR response is smooth and symmetric. The derivative peak-to-peak separation of 33 Oe converts to a half power linewidth of 57 Oe. The best linewidths from previous work have been in the 200-400 Oe range. The

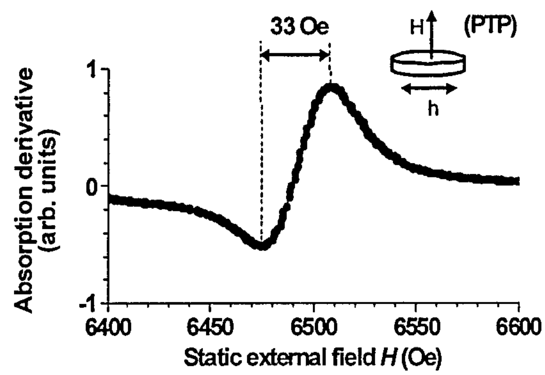

FIG. 12. Representative absorption derivative versus static external field H profile at 9.5 GHz on a 0.70 μm thick lithium zinc ferrite film. The inset indicates the field geometry, with a perpendicular-to-plane (PTP) field H and an in-plane microwave field h. The vertical dashed lines and the 33 Oe label indicate the usual "derivative" linewidth. [Y. Song, M. S. Grinolds, P. Krivosik, and C. E. Patton, J. Appl. Phys. 97, 103516 (2005).]

target single crystal linewidth is 2 Oe. Figure 13 shows data on the FMR field position as a function of the in-plane rotation angle ϕ. The four fold symmetry demonstrates the good epitaxial nature of the film.

g. High power properties of metallic ferromagnetic films

Even though the traditional material of choice for microwave devices is a ferrite or garnet in one form or another and of the sort discussed above, metallic thin films are receiving increasing attention for possible tunable filter applications. While metal films for such applications must, of necessity, be relatively thin, this is compensated to some degree by the high saturation induction. Permalloy (nominally 80%-20% Ni-Fe) and pure iron, for example, have $4\pi M_s$ values of 10 kG and 20 kG, respectively. The thin film device design can also be optimized to give low insertion loss and high isolation values that are comparable to those of ferrite based devices. Celinski and co-workers at the University of Colorado - Colorado Springs (UCCS) (Kuanr *et al.*, 2003), have developed respectable tunable band stop filters in the 5 - 30 GHz range based on both Permalloy and iron thin films.

To date, the CSU work has focused on the high power microwave response in Permalloy films, with a view to understand the fundamental spin wave instability processes that lead to the so called subsidiary absorption or low field loss and the saturation of the FMR. Figure 14 (An *et al.*, 2004) shows the basic high power effects. These data were obtained at 9.37 GHz on a 128 nm thick film with the mutually orthogonal static and microwave fields both in-plane. The solid circles show the low power FMR response. The open circles show the change when one goes to high power. One sees two effects, (1) a saturation and broadening of the FMR profile and (2) the appearance of a new loss region at low field. In these films, as with ferrites, this low field loss peak can severely affect the performance of off resonance devices. The extra loss at resonance can affect the performance of filters of the type developed at UCCS. A full discussion of these metallic film high power responses is beyond the scope of this brief summary. These responses (1) are non-classical, unlike the thermal foldover responses in YIG films discussed above, and (2) can be analyzed and understood on the basis of spin wave instability theory.

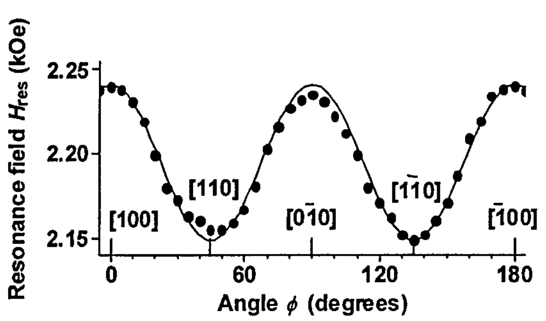

FIG. 13. Resonance field H_{res} as a function of the in-plane field angle ϕ relative to the in-plane [100] crystallographic direction for the (001) 0.70 μm thick lithium zinc ferrite film sample. The solid circles show the data and the solid curve shows a computed response based on the uniform mode FMR response for a (001) thin film with cubic anisotropy and a negative first order anisotropy constant. The principal in-plane directions are indicated along the horizontal axis. [Y. Song, M. S. Grinolds, P. Krivosik, and C. E. Patton, J. Appl. Phys. 97, 103516 (2005).]

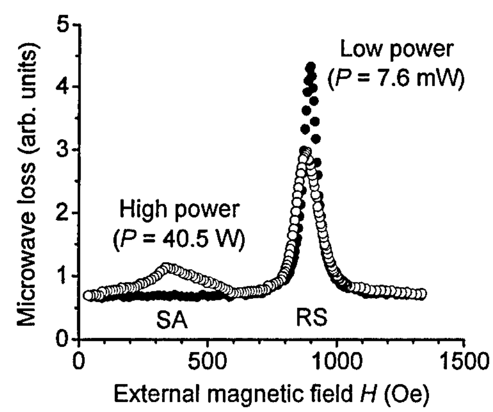

FIG. 14. Microwave loss versus the static external magnetic field H for a 128 nm thick Permalloy film for the in-plane static field configuration and pulse microwave excitation at 9.37 GHz. The solid and open circles denote data for a peak input power P to the cavity of 7.6 mW and 40.5 W, respectively. The RS and SA labels indicate the field regions for resonance saturation and subsidiary absorption, respectively. [S. Y. An, P. Krivosik, M. A. Kraemer, H. M. Olson, A.V. Nazarov, and C. E. Patton, J. Appl. Phys. 96, 1572 (2004).]

D. PUBLICATIONS, PRESENTATIONS, AND CITATIONS

1. Archival Publications:

ONR acknowledged:

"High power microwave properties of Zn-Y hexagonal ferrite - parallel pumping size effects," A. V. Nazarov, R. G. Cox, and C. E. Patton, J. Appl. Phys. **92**, 3890 (2002).

"Optimized pulsed laser deposited barium ferrite thin films with narrow ferromagnetic resonance linewidths," Y. Y. Song, S. Kalarickal, and C. E. Patton, J. Appl. Phys. **94**, 5103 (2003).

"Near theoretical microwave loss in hot isostatic pressed (hipped) polycrystalline yttrium iron garnet," A. V. Nazarov, D. Ménard, J. J. Green, C. E. Patton, G. M. Argentina, and H. J. Van Hook, J. Appl. Phys. **94**, 7227 (2003).

"Effect of the large magnetocrystalline anisotropy on the spin wave linewidth in Zn-Y hexagonal ferrite," A. V. Nazarov and C. E. Patton, J. Appl. Phys. **93**, 9195 (2003).

"Thermal microwave foldover and bistability in ferromagnetic resonance," Y. K. Fetisov and C. E. Patton, IEEE Trans. Magn. **40**, 473 (2004).

"High power ferromagnetic resonance and spin wave instability processes in Permalloy films," S. Y. An, P. Krivosik, M. A. Kraemer, H. M. Olson, A.V. Nazarov, and C. E. Patton, J. Appl. Phys. **96**, 1572 (2004).

"High field microwave effective linewidth in polycrystalline ferrites," N. Mo, Y. Y. Song, and C. E. Patton, J. Appl. Phys. **97**, 093901 (2005).

"Pulsed laser deposited single crystal Li-Zn ferrite films with low microwave loss, Y. Song, M. S. Grinolds, P. Krivosik, and C. E. Patton, J. Appl. Phys. **97**, 103516 (2005).

Total: 8

ONR acknowledged - in preparation:

"The low field microwave effective linewidth in polycrystalline ferrites," N. Mo, J. J. Green, P. Krivosik, and C. E. Patton, J. Appl. Phys.

"Intergranular interactions in Fe-Ti-N thin films," K. Srinivasan, J. Das, and C. E. Patton, J. Appl. Phys.

"Fundamental magnetic properties and structural implications for nano-crystalline Fe-Ti-N thin films, J. Das, S. S. Kalarickal, K. S. Kim, and C. E. Patton, Phys. Rev. B.

"Pulsed laser deposited barium ferrite films with low ferromagnetic resonance linewidths - plume position as a global property control parameter, J. Das, B. Griffin, and C. E. Patton, J. Appl. Phys.

"Temperature and frequency dependence of the ferromagnetic resonance linewidth in Fe-Ti-N Thin Films – Structural Implications," S. S. Kalarickal, K. S. Kim, J. Das, K. Alargov, and C. E. Patton, J. Appl. Phys.

"Classical theory of full spin wave dispersion bands, N. Mo and C. E. Patton, J. Appl. Phys.

"High power ferromagnetic resonance in thin Permalloy films - the steady state response, threshold modifications, and magnon scattering, P. Krivosik, K. Srinivasan, H. M. Olson, and C. E. Patton, J. Appl. Phys.

Total: 7

Other archival papers:

"Magnetostatic spin wave solitons in obliquely magnetized yttrium iron garnet films," Y. K. Fetisov and C. E. Patton, Radioteknika i Elektronika **48**, 210 (2003), in Russian [J. Comm. Tech. and Electronics **48**, 185-195 (2003)].

"Theoretical analysis of nonlinear pulse propagation in ferrite-dielectric-metal structures based on the nonlinear Schrödinger equation with high order terms," A. S. Kindyak, M. M. Scott, and C. E. Patton, J. Appl. Phys. **93**, 4739 (2003).

"Spatial recurrence for nonlinear magnetostatic wave excitations," M. M. Scott, B. A. Kalinikos, and C. E. Patton, J. Appl. Phys. **95**, 5877 (2003).

"Brillouin light scattering analysis of three magnon splitting processes in yttrium iron garnet films," C. Mathieu, V. T. Synogatch, and C. E. Patton, Phys. Rev. **B67**, 104402 (2003).

"Nonlinear damping of high power magnetostatic waves in yttrium iron garnet films," M. M. Scott, C. E. Patton, M. P. Kostylev, and B. A. Kalinikos, J. Appl. Phys. **95**, 6294 (2004).

"Spatial evolution of higher order microwave magnetic envelope solitons in yttrium iron garnet thin films," M. Wu, M. A. Kraemer, M. M. Scott, C. E. Patton, and B. A. Kalinikos, Phys. Rev. **B70**, 54402 (2004).

"Generation of dark and bright spin wave envelope soliton trains through self-modulational instability in magnetic films," M. Wu, B. A. Kalinikos, and C. E. Patton, Phys. Rev. Lett. **93**, 157207 (2004).

"Excitation of bright and dark envelope solitons for magnetostatic waves with attractive nonlinearity," M. M. Scott, M. P. Kostylev, B. A. Kalinikos, and C. E. Patton, Phys. Rev. **B71**, 174440-1 to 4 (2005).

"Fast pulse excited spatio-temporal spin waves in yttrium iron garnet thin films," M. Wu, B. A. Kalinikos, P. Krivosik, and C. E. Patton, J. Appl. Phys. **99**, 013901-1 to 5 (2006).

"Self-generation of chaotic solitary spin wave pulses in magnetic film active rings," M. Wu, B. A. Kalinikos, and C. E. Patton, Phys. Rev. Lett. **95**, 237202-1 to 4 (2005).

"Observation of spin wave soliton fractals in magnetic film active feedback rings," M. Wu, B. A. Kalinikos, L. D. Carr, and C. E. Patton, Phys. Rev. Lett. **96**, 187202-1 to 5 (2006).

"Ferromagnetic resonance linewidth in metallic thin films - comparison of measurement methods," S. S. Kalarickal, P. Krivosik, C. E. Patton, M. L. Schneider, P. Kabos, T. J. Silva, and J. P. Nibarger, J. Appl. Phys. **99**, 093909 1-7 (2006).

"Random generation of coherent solitary waves from incoherent waves," M. Wu, P. Krivosik, B. A. Kalinikos, and C. E. Patton, Phys. Rev. Lett. **96**, 227202-1 to 4 (2006).

Total: 13

2. Presentations

Presentations by Carl E. Patton:
Number of talks: 43, Invited: 38, Contributed: 5

"Low frequency losses in ferrite microwave devices," 47th Annual Conference on Magnetism and Magnetic Materials, Tampa, Florida, November 15, 2002. (Paper presented on behalf of Dr. Ernst Schloemann).

"Microwave magnetic envelope soliton formation from long input pulses in yttrium iron garnet thin films," 47th Annual Conference on Magnetism and Magnetic Materials, Tampa, Florida, November 15, 2002.

"Brillouin light scattering on spin wave excitations in magnetic thin films," Colloquium, City University of Hong Kong, January 28, 2003.

"Some quirks in precession dynamics - the anti-Larmor response," International Magnetics Conference, Boston, Massachusetts, April 3, 2003.

"Parametric pumping, nonlinear spin waves, and spin wave instability in Permalloy films," Lecture:
- National Institute of Standards and Technology Nanomagnetodynamics Workshop at the Summer Meeting of the National Storage Industry Consortium, Monterey, California, June 26, 2003.
- Special Colloquium, Department of Materials Science, University of Maryland, College Park, September 23, 2003.
- Special Colloquium, Department of Physics, Queens College CCNY, New York, New York, September 25, 2003.
- Special Colloquium, Free University of Berlin, Germany, January 19, 2004.
- Special Colloquium, University of Regensburg, Germany, January 20, 2004.
- Special Colloquium, Ruhr University, Bochum, Germany, January 26, 2004.

"Microwave envelope solitons in magnetic thin films,"
- Colloquium, Department of Applied Physics and Mathematics, Columbia University, New York, New York, September 24, 2003.
- Colloquium, Department of Physics, University of Nebraska, Lincoln, January 20, 2005.

"Microwave Ferrite Science and Technology," Colorado State University Materials Science Colloquium, Fort Collins, Colorado, September 29, 2003.

"Some informal and unofficial comments on phenomenological damping," The 9th Joint MMM-Intermag Conference, Anaheim, California, January 7, 2004.

"Spin wave instability, damping, and critical modes in Permalloy films," Electromagnetics Division Seminar, National Institute of Standards and Technology, Boulder, Colorado, February 17, 2004.

"Precession dynamics in magnetic thin films - extension to heads and media," Information Storage Industry Consortium (INSIC) Winter Meeting, San Diego, California, February 24, 2004.

"A romp through low and high power magnetic loss parameters and measurement techniques for microwave ferrites," Workshop on Modern Measurements of Ferrite Materials for Microwave and Millimeter Wave Devices, IEEE International Microwave Symposium 2004, Fort Worth, Texas, June 7, 2004.

"New materials and configurations for 10-100 GHz microwave devices," Invited lecture:

Workshop on New Technologies for Frequency Agile Microwave Circuits and Systems, IEEE International Microwave Symposium 2004, Fort Worth, Texas, June 7, 2004.

Rockwell Scientific, Thousand Oaks, California, July 27, 2004.

"Low and high power magnetic loss parameters and measurement techniques for microwave ferrites,"

Featured presentation, Advanced Microwave Ferrite Program Review Board Meeting, University of Idaho, Moscow, Idaho, August 31, 2004.

Invited lecture, University of Versailles, France, September 20, 2004.

"Losses in precessional dynamics - overview of physical relaxation processes," Lecture, Nexbias ultraswitch Summer School, Biarritz, France, September 12, 2004.

"Losses in precessional dynamics - phenomenological damping," Nexbias ultraswitch Summer School Lecture, Biarritz, France, September 13, 2004.

"Precessional dynamics in magnetic systems - I. Basic precession concepts. II. Phenomenological damping.

Seminar, Seagate Technology, Inc., Bloomington, Minnesota, January 13, 2005.

Seminar, Center for Materials Research and Analysis, University of Nebraska, Lincoln, January 21, 2005.

"Precessional dynamics in magnetic systems - basic concepts, physical relaxation processes, and phenomenological damping, Department of Electrical Engineering, University of Minnesota, Minneapolis, Special Workshop, January 14, 2005.

"Nonlinear ferromagnetic resonance, pulsed field precession dynamics, and spin wave loss in Ni-Fe films," Information Storage Industry Consortium (INSIC) Winter Meeting, Palo Alto, California, March 1, 2005.

"Self generation of solitary, chaotic, spin wave pulses," International Magnetics Conference, Nagoya, Japan, April 6, 2005.

"Phenomenological damping models as drive to equilibrium," International Magnetics Conference, Nagoya, Japan, April 7, 2005.

Invited workshop on precession dynamics, Toyota Technological Institute, Nagoya, Japan, April 11 - 13, 2005.

"Magnetic moments, torque, and gyroscopic precession"

"The torque equation of motion and ferromagnetic precession"

"Phenomenological damping in precessional dynamics"

"Spin wave modulational instability and spin wave envelope soliton generation in magnetic films," Joint Colloquium, Departments of Physics and Mathematics, University of Colorado at Colorado Springs, April 28, 2005.

"Nonlinear ferrite film microwave signal processing for advanced battlefield communications – physics and devices," U. S. Army Workshop on Advanced Active Thin Film Materials for the Next Generation of Meso-Scale Army Applications, Destin, Florida, May 11, 2005.

"Spin wave envelope solitons in magnetic film feedback rings," International Conference on Nonlinear Waves, Integrable Systems, and Applications, University of Colorado at Colorado Springs and at Boulder, June 6, 2005.

"Envelope solitons in magnetic films."

Condensed Matter Colloquium, Department of Physics, New York University, June 23, 2005.

Department Colloquium, San Francisco State University, October 31, 2005.

"Microwave magnetics materials and devices - review of projects and capabilities at Colorado State University" Guest Presentation, ONR Electronic Materials MURI Program Review on Epitaxial Multifunctional Materials and Devices, Boston, Massachusetts, June 29, 2005.

"Microwave materials and devices - challenges and needs in multiferroics," DARPA Workshop on Multiferroics and Magneto-Electric Heterostructures," Arlington, Virginia, June 30, 2005.

"GHz electromagnetic wave science and devices for advanced battlefield communications," ARO MURI Program review Meeting, Colorado Springs, Colorado, August 10, 2005.

"Effective linewidth in polycrystalline yttrium iron garnet (YIG)," ONR Electronic Materials Program Review Meeting, Red Bank, New Jersey, August 17, 2005.

"Effective linewidth - the FMR linewidth is not the while story," Colloquium, Department of Physics, University of Colorado at Colorado Springs, October 13, 2005.

"Vignettes on the CSU INSIC program - Part I. High power ferromagnetic resonance in metal films - new results and implications for switching. Part II. Fundamental properties of Fe-Ti-N films," Information Storage Industry Consortium (INSIC) Spring EHDR Meeting, San Diego, California, March 9, 2006.

Presentations by other group members:
Number of talks: 12, Invited: 0, Contributed: 12

"Optimized pulsed laser deposited Ba ferrite films with narrow ferromagnetic resonance linewidths," Y. Song, 47th Annual Conference on Magnetism and Magnetic Materials, Tampa, Florida, November 15, 2002.

"Ferromagnetic resonance, spin wave instability, and nonlinear damping at high power for Permalloy thin films.," S. Y. An, 47th Annual Conference on Magnetism and Magnetic Materials, Tampa, Florida, November 15, 2002.

"Subsidiary absorption and resonance saturation spin wave instability processes in Permalloy thin films – thickness effects and critical modes," P. Krivosik, 9th Joint MMM-Intermag Conference, Anaheim, California, January 6, 2004.

"High field microwave effective linewidth in polycrystalline ferrites – physical origins and intrinsic limits," N. Mo, 9th Joint MMM-Intermag Conference, Anaheim, California, January 6, 2004.

"Pulsed laser deposited single crystal LiZn ferrite films with narrow ferromagnetic resonance linewidths," Y. Song, 9th Joint MMM-Intermag Conference, Anaheim, California, January 6, 2004.

"Ferromagnetic relaxation in Permalloy thin films – a consistency check for ferromagnetic resonance technique and pulsed inductive magnetometry, " S. S. Kalarickal, 49th MMM Conference, Jacksonville, Florida, November 8, 2004.

"Two-magnon scattering processes in magnetic thin films – a simple and mathematically tractable model," P. Krivosik, 49th MMM Conference, Jacksonville, Florida, November 8, 2004.

"Origin of the low field microwave effective linewidth in ferrites," N. Mo, 49th MMM Conference, Jacksonville, Florida, November 8, 2004.

"Ferromagnetic resonance vs. temperature in metal/native oxide multilayers - evidence for a low temperature rotatable anisotropy," M. A. Wittenauer, 49th MMM Conference, Jacksonville, Florida, November 8, 2004.

"Spin wave envelope solitons in magnetic film feedback rings," M. Wu, International Conference on Nonlinear Waves, Integrable Systems, and Applications, University of Colorado at Colorado Springs and Boulder, June 4, 2005.

"The cloning of magnetostatic wave pulses by parametric pumping," K. R. Smith, 50th MMM Conference, San Jose, California, October 30, 2005.

"Generation of period tunable spin wave envelope soliton trains through induced modulational instability," M. Wu, 50th MMM Conference, San Jose, California, October 30, 2005.

3. Citations from Sec. C - 2:

(An *et al.*, 2004) "High power ferromagnetic resonance and spin wave instability processes in Permalloy films," S. Y. An, P. Krivosik, M. A. Kraemer, H. M. Olson, A.V. Nazarov, and C. E. Patton, J. Appl. Phys. **96**, 1572 (2004).

(Fetisov and Patton, 2004) "Thermal microwave foldover and bistability in ferromagnetic resonance," Y. Y. K. Fetisov and C. E. Patton, IEEE Trans. Magn. **40**, 473-482 (2004).

(Gurevich *et al.*, 1999) A. G. Gurevich, A. V. Nazarov, O. A. Chivileva, and V. V. Petrov, Phys. Solid State **41**, 1513 (1999).

(Gurevich and Melkov, 1996) *Magnetization Oscillations and Waves*, (CRC Press, Boca Raton, 1996).

(Karim *et al.*, 1993) " Frequency dependence of the ferromagnetic resonance linewidth and effective linewidth in manganese substituted single crystal barium ferrite," R. Karim, S. D. Ball, J. R. Truedson, and C. E. Patton, J. Appl. Phys. **73**, 4512 (1993).

(Kuanr *et al.*, 2003) "High Frequency Band Stop Magnetic Filters," B. K. Kuanr, Z. Celinski, and R. E. Camley, Appl. Phys. Lett. **83**, 3969 (2003).

(Mo *et al.*, 2004) "Origin of the low field microwave effective linewidth in ferrites," N. Mo, J. J. Green, P. Krivosik, and C. E. Patton, 49th Conference on Magnetism and Magnetic Materials, 8 - 11 November 2004.

(Mo *et al.*, 2005) "High field microwave effective linewidth in polycrystalline ferrites," N. Mo, Y. Song, and C. E. Patton, J. Appl. Phys. **97**, 093901 (2005).

(Nazarov *et al.*, 2003a) "Effect of the large magnetocrystalline anisotropy on the spin wave linewidth in Zn-Y hexagonal ferrite," A. V. Nazarov and C. E. Patton, J. Appl. Phys. 93, 9195-9201 (2003).

(Nazarov *et al.*, 2003b) "Near theoretical microwave loss in hot isostatic pressed (hipped) polycrystalline yttrium iron garnet," A. V. Nazarov, D. Ménard, J. J. Green, C. E. Patton, G. M. Argentina, and H. J. Van Hook, J. Appl. Phys. **94**, 7227 (2003).

(Schloemann, 1958) E. Schloemann, J. Phys. Chem. Solids **6**, 242 (1958).

(Song *et al.*, 2003) "Optimized pulsed laser deposited barium ferrite thin films with narrow ferromagnetic resonance linewidths," Y. Y. Song, S. Kalarickal, and C. E. Patton, J. Appl. Phys. **94**, 5103 (2003).

(Song *et al.*, 2005) "Pulsed laser deposited single crystal Li-Zn ferrite films with low microwave loss, Y. Song, M. S. Grinolds, P. Krivosik, and C. E. Patton, J. Appl. Phys. 97, 103516 (2005).

E. ACKNOWLEDGEMENTS

The Principal Investigator is indebted to his research associates and graduate students in the Magnetics Group at Colorado State University for their energetic and insightful work on the current program and for their ideas and suggestions that have gone into the present proposal. Professor Yuri Fetisov, Professor Boris Kalinikos, Dr. Sung-Yong An, Dr. Jaydip Das, Dr. Sangita Kalarickal, Dr. Igor Kalinichenko, Dr. Kyoung-Suk Kim, Dr. Michael Kraemer, Dr. Pavol Krivosik, Dr. Nan Mo, Dr. Alexi Nazarov, Dr. Young Yeal Song, Dr. Kumar Srinivasan, Dr. H. Jerrold Van Hook, Dr. Michael Wittenauer, Dr. Mingzhong Wu, Mr. Michael Grinolds, Ms. Heidi Olson, and Mr. Kevin Smith produced most of the results described herein. The participation of Co-Principal Investigator, Dr. Jerome J. Green (Raytheon Company, retired) in the program, although short in time, has been long in results. His time spent in mentoring group members and providing guidance to the program is very much appreciated. The group as a whole is also indebted to Dr. Wittenauer for providing single crystal materials of Ba-M and Zn-Y hexagonal ferrite from a previous ONR program at Purdue University. Dr. Van Hook of Raytheon Company (retired) and Mr. Gil Argentina and Mr. Munson Chen of Pacific Ceramics contributed in critical ways to the HIPPED YIG work.